MEETING 2002 OCEAN SCIENCES MEETING

Of Salt Fingers, Rot, and a Flip-Flop in the Sea

Oceanographers made more than 2200 presentations at last month's Ocean Sciences Meeting from 11 to 15 February, sponsored by the American Geophysical Union and the American Society of Limnology and Oceanography. But three examples may give the flavor of the highly interdisciplinary Honolulu gathering: the "fingered, not stirred" mixing of the ocean, the "rotten steppingstone" route of mussels into the deep sea, and a mood swing in the North Pacific.

Salt Fingers Mix the Sea

To make a great martini, you have to mix it well. But as James Bond knows, there's more than one way to mix a drink. Oceanographers have long wondered what powerful analogs of a cocktail shaker or swizzle stick are at work combining the ingredients of the sea, mingling warmer waters with colder, saltier with fresher. Three decades ago, theory and then dogged observation established that large bodies of water can mix without stirring or shaking, as interweaving fingers of water flow up and down between distinct layers of seawater. Driven solely by thermodynamics, this "salt fingering" was real enough. But was it powerful enough to be a player in ocean mixing?

At the meeting, physical oceanographers Raymond Schmitt, James Ledwell, John Toole, and Kurt Polzin of the Woods Hole Oceanographic Institution (WHOI) in Massachusetts reported the first direct measurement of the power of salt fingering. By following the spread of an inert chemical tracer, they found that salt fingering was mixing waters east of Barbados 10 times more effectively than stirring by currents and eddies was. "It's a nice vindication of salt-finger models" of mixing, says Schmitt.

The decades-long pursuit of ocean mixing had long frustrated physical oceanographers. They could see that mixing happens. Sun and wind drive globe-girdling currents that ultimately send cold, dense water into the deep sea, but the sea has not filled to the brim with cold water. Instead, in some places cold currents must rise to mix with warmer, shallower waters and complete the circulation loop. But when oceanographers measured the amount of turbulent stirring in most parts of the ocean, it was a tenth of what was needed. Finding where and how the sea mixes is crucial to understanding, among other things, how the ocean cools the planet by taking up heat as well as absorbing the greenhouse gas carbon dioxide.

Some oceanographers, and Schmitt in particular, saw salt fingers as part of the solution. Where warm, salty ocean water lies above cold, fresher water, as it does in the tropics and subtropics, centimeter-wide salt fingers were seen mixing bodies of water hundreds of kilometers across without stirring. The stirring takes place because heat diffuses 100 times faster than salt in seawater. Where salt fingering occurs, centimeter-wide columns of water stack side by side, forming layers a few tens of centimeters thick. The columns form a sort of heat exchanger in which warm, salty water in some of the "tubes" passes its heat to adjacent colder, fresher water, becoming heavier and sinking. Meanwhile, the colder, fresher water in adjacent tubes warms up, lightens, and rises. The variation of temperature and salinity across salt fingers persuaded Schmitt that the tubes were doing some serious mixing, but others remained unconvinced.

No swizzle stick. This turbulence sensor helped show that salt fingering, not stirring, was mixing tropical waters.

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East of Barbados, layers of salt fingers made an obvious target for the WHOI group. In addition to measuring turbulent mixing and water properties, the researchers traced the movement of a patch of water as it mixed over more than 300 days last year. In January 2001, they released 175 kilograms of a tracer, liquid sulfur hexafluoride, from a sled towed at a constant depth of 400 meters as it crisscrossed a 25-kilometer-square patch of ocean. The chemical formed a 20-meter-thick layer between two layers of salt fingers. When the group came back in November, the tracer—which can be easily detected even if diluted to 1 gram in a cubic kilometer of seawater (*Science*, 8 January 1993, p. 175)—had mixed more than 120 meters above and below the release level. That was 10 times more than the turbulent stirring measured there could have caused, says Schmitt.

"The result was pretty definitive," says physical oceanographer Robert Pinkel of the Scripps Institution of Oceanography in La Jolla, California. The question now becomes just how prevalent salt fingering is, he says. It's common in the tropics and subtropics, under outflow tongues of water like the current that flows from the Mediterranean at Gibraltar, and at weatherlike "fronts" in polar regions, Schmitt notes. "I think it could be quite substantial" worldwide, he says. Now that the mixing power of salt fingering has been demonstrated, the search should be on.

–RICHARD A. KERR

Mussels on the Move

Sulfur-spewing hydrothermal vents at the ocean floor may seem like a strange home for surf-loving animals such as mussels, but more than 14 species of mussels thrive on vents thousands of meters under the Atlantic and Pacific. Scientists have linked the deep dwellers to their shallow cousins since the mid-1990s, but how mussels made the evolutionary trip from seashore to ocean bottom was mostly speculation until now. At the meeting, Amy Baco and Craig Smith of the University of Hawaii, Manoa, and colleagues described how they used mitochondrial genes to chart the mussels' evolutionary course. Shallow-water mussels, they showed, hopped from sunken wood to whale bones before settling in to cold bottom seeps—regions where hydrocarbons or salts ooze out of the ocean floor—and hydrothermal vents.

Smith first proposed that sunken organic remains might serve as a way station for mussels colonizing the deep back in the 1980s, when he noticed mussels growing on rotting whale bones. At the meeting, Smith described how colonies that set up shop on whale bones can last for decades, sending out their free-swimming larvae to colonize other organic remains. Such environments are more common than one might think: Smith estimates that nutrient-rich whale skeletons crop up every 9 km on average along gray

Ocean oasis. One-centimeter-long *Idas washingtonia* mussels colonize a whale rib on the ocean floor off California.

whale migration routes, and sunken, waterlogged wood is common off forested coasts.

Studies of mussel nuclear DNA eventually unearthed a common ancestor for the mussel species from sunken wood and from whale bones, vents, and seeps. But the nuclear DNA hadn't changed enough between the species to tell when the different populations diverged. Because mitochondrial DNA mutates faster than nuclear DNA, Baco sequenced two mitochondrial genes from three to four species from each of the four environments—a thorough species spread, comments marine biologist Rick Gustafson of the National Marine Fisheries Service in Seattle. The evolutionary tree Baco and Smith drew from these genes confirmed that most deep-water species moved from rotting wood to whale falls, then to seeps, and finally to hydrothermal vents.

Evolutionary biologist Robert Vrijenhoek of the Monterey Bay Aquarium Research Institute in Moss Landing, California, believes that clams and other animals may echo the evolutionary path Baco described. But he cautions that the progression from surface to bottom may not be a one-way street. Once the mussels have developed the ability to survive down deep, there may be quite a bit of crossover between vents and seeps, he says. "Other evidence," he adds, "suggests mussels may be a bit more clever and opportunistic bunch," moving back and forth between vents and seeps. But the general trend is clear, Baco says: A rotting set of steppingstones led mussels to the bottom of the sea.

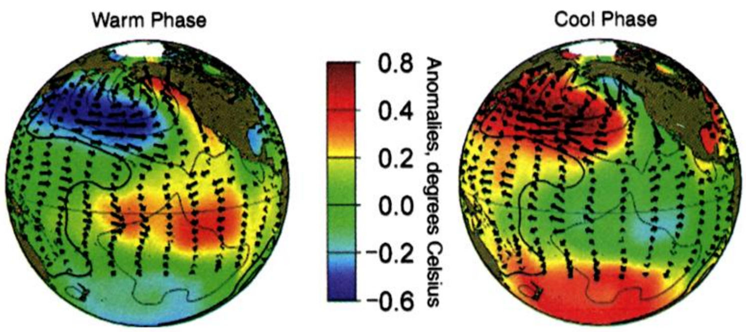
–KATIE GREENE

Coastal Cool-Down

Over the past century, the North Pacific Ocean has swapped hats every 20 to 30 years, exchanging a cool cap for warm wool—or vice versa—as sea surface temperatures rise or fall along the coast of North America and in the tropics. This change in the mean state of the ocean thermostat—called the Pacific Decadal Oscillation (PDO)—is only one symptom of a broader climate change that influences weather patterns across North America and might jack up or down the number of El Niños in a given decade.

At the meeting, physical and biological oceanographers gathered to discuss the 1999 flip in sea surface temperatures, which chilled waters along the edge of the Pacific and in the tropics, and its impact on ecosystems off the western coast of North America. The driving forces behind the PDO are still being debated, and the recent shift may be temporary background noise in the climate system, says atmospheric scientist Nathan Mantua of the University of Washington, Seattle. But even if the waters quickly warm up again, the 3-year chill has already sharply affected marine life, says climate researcher Arthur Miller of the Scripps Institution of Oceanography in La Jolla, California: "The biology is telling us loud and clear that things have changed in the Pacific Ocean."

The last major regime shift, in 1976, took oceanographers by surprise. Most believed the ocean had only one long-term stable state. It took them almost a decade to recognize the 1976 change as a shift between two equally valid equilibrium states for the ocean. Fish catches gave the first hint. After 1976, a booming salmon fishery off the coast of Oregon crashed even as Alaskan salmon surged, suggesting that the temperature changes, and changes in the amount of nutrient-laden water brought up to the coast from the deep, had altered the availability of food.



Some like it cold. Average ocean temperatures in the Pacific flipped from hot (left) to cold (right) in 1999, affecting ecosystems.

Oregon coho salmon began to recover in 1999, inching out of the extremely low survival rates that had plagued the fishery through the 1990s. Upwelling—the process of bringing up deep water to the coast—had picked up as temperatures dropped. But this time around, oceanographers are poised to understand changes not just to salmon but also to the food web that supports them.

Bill Peterson, a biological oceanographer at the National Marine Fisheries Service in Newport, Oregon, has been monitoring the population of euphausiids (commonly known as krill) off the Oregon coast every 2 weeks since 1996. These large zooplankton make up much of the salmon's ocean diet. In the year beginning in 1999, the average water temperature off Oregon plummeted 5 degrees Celsius, and Peterson described the dramatic boom in both krill and the copepods they feed on. "It happened practically overnight," he said. The warm-water species that had dominated Oregon's coastal ecosystem for a decade disappeared, replaced by species normally seen farther north.

Frank Schwing, an oceanographer at the Pacific Fisheries Environmental Laboratory in Pacific Grove, California, said at the meeting that the changes in circulation in 1999 may have increased the flow of nutrients to the bottom of the food chain, triggering an explosion in the amount of life the waters could support. And Elizabeth Logerwell, a fisheries biologist at the Alaska Fisheries Science Center in Seattle, presented results from a model coupling ocean physics with bottlenecks in salmon populations. According to the model, she says, the increase in salmon population could be due either to the newly available zooplankton or to the fall in water temperatures, because many of the salmon's ocean predators prefer warmer waters.

Whatever their cause, the changes to coastal ecosystems may be short-lived. Physical oceanographer Michael McPhaden of the Pacific Marine Environmental Laboratory in Seattle suggests that the pattern might merely be evidence of a particularly long and strong La Niña—a cold upwelling in the tropics that sometimes follows an El Niño. "The 1997–98 El Niño was the largest on record," he says, so it's not a stretch to assume that the subsequent La Niña, a strong one, was also surprisingly persistent and far-reaching. Peterson, however, is unconvinced. "Three, 4, 5 years—how long does it need to last before it's called a shift?" he asks. Most Las Niñas persist only for a year or two, he argues, and these conditions have been around for 3.5 years.

Forecasters suggest that an El Niño is brewing in the Pacific even now. The experimental parameters are changing again, and the results may knock the oscillation back into its warm state. "History can only help so much in predicting the future," says Mantua. "In this complex system, nature is always surprising us."

–K.G.

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